Volume V

Appendix G.5

Vehicle Data Mapping (VDM) Team Final report, Jun 13, 2003

This Appendix contains NSTS-37383 Vehicle Data Mapping Team Final Report in Support of the *Columbia* Accident Investigation, 13 June 2003.

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NSTS-37383

Vehicle Data Mapping (VDM) Team Final Report

in support of the *Columbia* Accident Investigation

June 13, 2003

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Table of Contents

Executive Summary

The Vehicle Data Mapping (VDM) Team was created to support the Orbiter Vehicle Engineering Working Group (OVEWG) investigation of the OV-102/*Columbia* accident that occurred during the STS-107 mission on February 1, 2003. The VDM team charter included the creation of unique and innovative data display products that aid in understanding the hardware configuration, sensor response data, and complex sequence of events during *Columbia's* entry.

In meeting this charter, approximately 125 personnel from NASA, Boeing, USA, and multiple support contractors from around the country produced seven major products and six supporting products in accordance with the VDM team product flowchart contained in Appendix A. Four special activities related to these products and encompassed by the VDM team charter were also pursued. All of these products and activities are discussed in detail in this report, along with related findings generated by the VDM team during this effort.

Due to the large volume of data produced by the VDM team, this report is best reviewed from the VDM team share drive or a compact disk (CD) containing all related product files, thus enabling embedded hyperlinks to work properly and maximizing data availability and organization. Accordingly, the planned method of distribution for this report is a CD. Note that a readme file is included to explain the general content and provide key usage instructions for the final report.

1.0 INTRODUCTION

The Vehicle Data Mapping (VDM) Team, headquartered at Johnson Space Center (JSC) and lead by NASA-JSC-EP/Gene Grush, was created to support the Orbiter Vehicle Engineering Working Group (OVEWG) investigation of the OV-102/*Columbia* accident that occurred during the STS-107 mission on February 1, 2003. The VDM team charter was as follows:

- To perform data collection, organization, and analysis for select vehicle parameters during entry.
- To research sensor installation details, wire routings, and power and signal conditioning configurations for associated instrumentation.
- To perform testing as required to anchor analytical models and define failure modes/signatures for associated instrumentation.
- To create unique and innovative data display products that aid in understanding the hardware configuration, sensor response data, and complex sequence of events during entry.

In general, the VDM team did not provide detailed interpretation of the flight data. Instead, the existing Problem Review Team (PRT) for each Orbiter subsystem performed this task with oversight from the Data Review and Timeline Reconstruction Team, who then used the results as an input to the master entry timeline. One exception, discussed later in this report, involved analyzing the timing and failure signatures of certain Orbiter sensors to identify trends and patterns in the data.

In meeting the VDM team charter, seven major products and six supporting data generation/gathering products were produced in accordance with the VDM team product flowchart contained in Appendix A. Four special activities related to these products and encompassed by the VDM team charter were also pursued. All of these products and activities are discussed in this report. To maximize efficiency and accountability, the VDM team structure and action tracking system were product oriented, including the assignment of a lead engineer for each product. To organize and control VDM team products and inputs, a VDM team headquarters (building 15, room 131) was established for meetings/telecons and display/storage of hardcopy data. A VDM team share drive was also established on a JSC server for display/storage of electronic files.

Over a 4-month period, approximately 125 personnel from NASA, Boeing, and United Space Alliance (USA) at JSC, Kennedy Space Center (KSC), Marshall Space Flight Center (MSFC), and Huntington Beach (HB), plus technical support personnel from Analytical Graphics, Inc., GHG Inc., IMC Incite, Lockheed Martin, Muniz Engineering, Inc. (MEI), Information Dynamics, Inc. (IDI), and SAIC, Inc., responded to action items and produced the products described in this report. A comprehensive list of VDM team members, action items (98 total), and action item response files is contained in Appendix B. During this process, the VDM team provided regular status briefings to the OVEWG, records of which are contained on the VDM team share drive. Similar or supplemental information was also provided directly to the *Columbia* Accident Investigation Board (CAIB) in several instances upon request.

2.0 PURPOSE AND SCOPE

This report is intended to provide final documentation of the VDM team products and findings. Due to the large volume of data produced by the VDM team, this report is best reviewed from the VDM team share drive or a compact disk (CD) containing all related product files, thus enabling embedded hyperlinks to work properly and maximizing data availability and organization. Accordingly, the planned method of distribution for this report is a CD.

3.0 PRODUCTS AND SPECIAL ACTIVITIES

In accordance with the VDM team product flowchart contained in Appendix A, seven major products, six supporting data generation/gathering products, and four special activities were created and pursued to help document, visualize, and comprehend the data associated with *Columbia's* entry on STS-107. The major source of flight data used for this effort included telemetry data from the Operational Instrumentation (OI) sensors and Orbiter Experiment (OEX) recorder data from the Modular Auxiliary Data System (MADS) sensors. This data was obtained in hardcopy and/or electronic form directly from the Mission Evaluation Room (MER) via formal data requests. Also, as mentioned previously, a key input to many VDM team products and activities was the master entry timeline from the Data Review and Timeline Reconstruction Team, which was used for identification and annotation of key events.

Unless otherwise specified for individual products or activities, ending times for OI sensor data include loss of signal (LOS) at Greenwich Mean Time (GMT) 2003/032:13:59:32.136 (data set referred to as “107 data”) and post-LOS at GMT 2003/032:14:00:31.102 (data set referred to as “107-edit data”). Similarly, the ending time for MADS sensor data is GMT 2003/032:14:00:14.290 (data set referred to as “OEX data”), with entry interface (EI) occurring at GMT 2003/032:13:44:09.000 (frequently used as a point of reference).

VDM team efforts initially focused on OI sensor data from the vehicle. The first OI indications of off-nominal performance involved a hydraulic line temperature on the inboard sidewall (Yo-105) of the left wheel well (V58T1703A, LMG Brake Line Temp D) at GMT 2003/032:13:52:17. Subsequently, other OI sensors began showing off-nominal trends. Of these, particular attention was given to the following 14 OI sensors (seven left wing, seven left wheel well) that went off-scale low (OSL) or unexpectedly changed state (starting at GMT 2003/032:13:52:56) prior to LOS:

Failure Order	MSID	Description	Sensor Location	Panel/ Connector	Mode
1	V09T1006A	LH Inbd Elev Lwr Skin Temp	Wing	Glove/P105	OSL
2	V58T0157A	Hyd 1 LH Inbd Elvn Actr Rtn Ln T	Wing	Glove/P105	OSL
3	V58T0394A	Hyd Sys 3 LOE Rtn Ln T	Wing	Glove/P105	OSL

4	V58T0257A	Hyd 2 LH Inbd Elvn Actr Rtn Ln T	Wing	Glove/P105	OSL
5	V58T0193A	Hyd Sys 1 LOE Rtn Ln T	Wing	Glove/P105	OSL
6	V09T1002A	LH Lwr Wing Skin Temp	Wing	Glove/P105	OSL
7	V09T1024A	LH Upr Wing Skin Temp	Wing	Glove/P105	OSL
8	V51P0570A	MLG LH Outbd Tire Press 1	W-well	W-well/P87	OSL
9	V51P0571A	MLG LH Inbd Tire Press 1	W-well	W-well/P87	OSL
10	V51T0574A	MLG LH Outbd Wheel Temp	W-well	W-well/P89	OSL
11	V51P0572A	MLG LH Outbd Tire Press 2	W-well	W-well/P89	OSL
12	V51T0575A	MLG LH Inbd Wheel Temp	W-well	W-well/P87	OSL
13	V51P0573A	MLG LH Inbd Tire Press 2	W-well	W-well/P89	OSL
14	V51X0125E	LH MLG Downlock Prox	W-well	W-well/P59	State

After the OEX recorder was recovered, attention was shifted to the MADS sensor data that provided 600+ additional pressure, temperature, and strain measurements of interest to the investigation, the first of which (V12G9921A, Left Wing Front Spar Strain) began showing signs of off-nominal performance at GMT 2003/032:13:48:39, approximately 3:38 sec before the first off-nominal OI sensor reading was detected.

The following sections in this report describe each VDM team product and special activity in detail. A complete list of these items is as follows:

- VDM-P01: 3D Full Animation Event Sequence Playback
- VDM-P02: Physical Mockup
- VDM-P03: 3D Graphical Events Sequence
- VDM-P04: 2D Static Storyboard
- VDM-P05: 2D Graphical Events Sequence
- VDM-P06: 3D CAD Modeling
- VDM-P07: Wire Routing / Sensor Placement Reconstruction
- VDM-P08: Events Timeline
- VDM-P09: Instrumentation Listing and Sensor Location
- VDM-P10: Sensor Signal Characterization for Failure Scenario
- VDM-P11: Structure / Installation Drawings
- VDM-P12: Wire Routing Details
- VDM-P13: Closeout Photos
- VDM Team ASA4 Anomaly Assessment
- VDM Team Testing
- VDM Team Leading Edge Wire Run Assessment
- Miscellaneous Tasks

3.1 VDM-P01: 3D Full Animation Event Sequence Playback

Product VDM-P01 is a digital video disk (DVD)-based movie/animation displaying telemetry data from select OI pressure and temperature sensors in the left wing, wheel well, and fuselage areas during entry. As of this writing, rev 2 is the latest version of the DVD, which conforms to rev 15 of the master entry timeline and rev 5 of product VDM-P05 (2D Graphical Events Sequence). As such, all animation sequences run from GMT 2003/032:13:51:00.000 to GMT 2003/032:14:00:31.000. In addition, a total of 39 OI sensors are depicted in the CAD model used to create this product. A complete list of these sensors is contained in Appendix C. Note that this product does not attempt to visualize specific failure scenario sequences (e.g. hot gas plumes, structural deflections, debris shedding, etc.) due to the complex and speculative nature of these details, although similar computer graphics techniques could be employed for this purpose if desired.

The following key inputs were used to generate this product:

- Product VDM-P04: 2D Static Storyboard (including OI sensor data from the MER)
- Product VDM-P05: 2D Graphical Events Sequence
- Product VDM-P06: 3D Orbiter CAD models
- Product: VDM-P07: Wire Routing/Sensor Placement Reconstruction
- Product VDM-P12: Wire Routing Details
- Master entry timeline

The product contains the following main computer graphics sequences:

- A "flythrough" of the left wing and wheel well areas allowing user familiarization with the vehicle physical configuration and geometry. Wing structure, wire runs and sensors, and wheel-well contents are all depicted in detail. Due to their small size, the sensors called out in the master entry timeline are represented as "balloons." Minor license was taken in the X-Y-Z positioning of the sensor balloons to ensure that they would be visible with the camera angles selected. Callouts and highlighting are employed to identify relevant features.

- A wing plan-form sequence showing the left side of the vehicle, including the fuselage sidewall. When selected, this sequence progresses in real time from a point prior to the onset of anomalous sensor indications during the STS-107 entry. A digital clock supplemented by an analog timeline display indicates current time. Sensor temperature and pressure indications are represented by color changes of the balloons: green representing nominal indications, yellow-orange-red representing increasingly above-nominal indications, and light-medium-dark blue representing below-nominal indications. White and black are used to indicate off scale high (OSH) and OSL, respectively, while gray indicates a sync/data loss. A side view of the Orbiter in an inset window illustrates vehicle attitude and Reaction Control System (RCS) thruster and aerosurface activity (aerosurface positions are exaggerated for visibility), and a simplified ground track plot indicates geographic location. Captions are superimposed to call out significant events from the entry timeline.

- A wheel well close-up sequence providing an enlarged view of the left wheel well, including the landing gear structure, hydraulic lines, and wire runs. The same balloon color change conventions used in the wing plan form sequence are employed here.

- A trajectory/ground track sequence with four sub-windows: one for timeline and caption data, an Orbiter side view comparable to the plan form view, a "gun camera" (camera trailing behind the Orbiter) view to further enhance visualization of Orbiter attitude, and an augmented ground track in aeronautical map format.

A menu on the DVD allows the user to select between these various animation sequences. Standard DVD angle functions allow the user to switch between the wing plan form, wheel well, and trajectory sequences in real time.

The first three sequences described above were created in the Integrated Graphic Operations and Analysis Laboratory (IGOAL) at JSC using an in-house developed application called Enigma, with 3D solid models of the Orbiter created in Pro/Engineer under product VDM-P06 (3D CAD Modeling). The fourth sequence was also created at JSC (with significant technical support from Analytical Graphics, Inc.) using Satellite Tool Kit (STK) software. Special graphics features and unique data intervals related to the use of STK are as follows:

- Animations of the Orbiter's attitude and trajectory over the Earth surface, including RCS and aerosurface activity.
- Separate "gun camera" and "right wingtip" (camera looking towards the Orbiter right side) views.
- Ground track views ranging from simplified maps showing only the Pacific coastline and U.S. state borders to fully detailed aeronautical maps.
- Special captions denoting significant events from the master entry timeline.

Note that all STK features/views are terminated at LOS+5 sec (GMT 2003/032:13:59:37.396), with interpolation used to represent sensor data during the brief communication dropout periods included in the master entry timeline.

The Enigma and STK output files were originated in AVI format. The individual caption, aeronautical map ground track, and STK gun camera and wingtip windows were integrated into one "quad view" window using Discrete Logic Combustion software. Subsequent compression and reformatting to MPEG2 format was performed to support DVD authoring using Spruce Maestro software (with significant technical support from IMC Incite for nonlinear editing).

One of two known issues with the current rev 2 version of the VDM-P01 DVD is that captions were inadvertently omitted from the wing plan form sequence. These captions are present on all other sequences. The other issue is that the color-coding for the Environmental Control and Life Support System (ECLSS) nozzle temperature sensors on the forward fuselage was erroneously scaled. Rev 3 of the DVD is in now in work to correct these two issues, begin earlier in the entry profile (GMT 2003/032:13:48:00.000), and conform to rev 16 of the master entry timeline. However, it still will not contain any MADS sensor data.

An organized list of all electronic files on the VDM team share drive related to product VDM-P01 and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report. In the case of product VDM-P01, the product itself is a DVD and all files contained therein are duplicated on the VDM team share drive. As of this writing, the large number of intermediate source files used in creating the DVD are managed individually and do not reside in either location.

3.2 VDM-P02: Physical Mockup

Product VDM-P02 is 1/10 scale physical mockup of the Orbiter left wing that includes major structural components such as wing ribs and spars, wing leading edge (WLE) spars, partial fuselage bulkheads, wheel well and landing gear elements, and wire harnesses associated with select OI sensors. A total of 28 OI sensors are depicted in the mockup, including 8 pressures and 9 temperatures associated with the tires and hydraulic system lines/components in the wheel well; 2 skin temperatures in the wing; 1 bondline temperature on the mid-fuselage sidewall; and 8 hydraulic line/component temperatures in the elevon coves. A complete list of these sensors is contained in Appendix C.

Despite structural elements being present, the mockup does not attempt to present a highly accurate and detailed structural model of the wing. It also does not include wing skin, Thermal Protection System (TPS) components, aerosurface or landing gear actuators, fluid lines, or any MADS sensors and associated wire runs. Instead, the mockup was built early in the investigation when detailed drawings were first becoming available and OI sensor data was initially being analyzed. Therefore, the mockup represents a quick-response solution to providing a reasonably detailed physical model that could be used as an aid to the visualization of major components and key wire harnesses, along with the physical relationships between them.

Several key inputs were used to generate this product:

- Product VDM-P06: 3D CAD Modeling
- Product VDM-P12: Wire Routing Details
- Product VDM-P13: Closeout Photos

The mockup was constructed as follows:

- Prints of the major structural spars and cross sections at the ribs were plotted at 1/10 scale. These prints were applied to 3/16” foam-core single-sided adhesive board. This was cut to finished size using the prints as a guide for their outer shape. Slots were cut at each intersection to allow the ribs and spars to slip together. As updated versions of a spar or rib cross section became available, the part was re-plotted and affixed to a new board. Then the new part would replace the older part. A functional landing gear assembly was also fabricated using plastic and foam to provide realistic structure for the attachment of select OI sensors.

- Wire runs for OI sensors shown were modeled with a variety of materials, including multicolored micro-gauge wires formed into bundles and 20 gauge insulated wires with color coding that matched the color scheme in use at the time of model construction. The OI sensors depicted on the mock-up include the mockup are referenced in Appendix C.

- For ease of transport, the wing model was built in two sections: from the 1365 spar at the elevon cove to the 1009 spar in the wing glove just forward of the wheel well, and from the 1009 spar to the 807 bulkhead at the wing chine interface.

The resulting mockup was used routinely during meetings, discussions, briefings, and throughout the VDM team investigation process to better visualize physical relationships and potential fluid flow paths through the left wing. The mockup was also provided to the CAIB upon request for temporary use while more detailed and accurate versions were being built to CAIB specifications. These improved mockups used similar construction techniques but slightly different materials, including clear polycarbonate backing for the wing rib sections to improve appearance, fidelity, and handling tolerance. They also included numerous TPS elements and many more sensors, had better internal vent path representations, and went further forward on the vehicle.

An organized list of all electronic files on the VDM team share drive related to product VDM-P02 and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.3 VDM-P03: 3D Graphical Events Sequence

Product VDM-P03 no longer exists in the VDM team product flowchart. Its intent is captured by products VDM-P04 (2D Static Storyboard) and VDM-P05 (2D Graphical Events Sequence).

3.4 VDM-P04: 2D Static Storyboard

Product VDM-P04 refers to plots of relevant sensor data coupled with maps of vehicle hardware that emphasize the communication of overall vehicle status information during the last hour of the STS-107 mission. Above all, this product attempts to present the flight data in an unbiased and non-timeline format that is unrelated to any given failure scenario. The finished product consists of the following sub-elements:

- A five-sheet E-size (34 in x 44 in) poster displaying relevant sensors and associated data plots to illustrate performance trends. The first two sheets (S1, S2), created early in the investigation, contain OI pressure and temperature sensor locations, data plots, and a comparison between left and right sides of the vehicle on STS-107 through LOS. The last three sheets (S3, S4, S5), created later in the investigation after the OEX recorder was recovered, contain MADS pressure, temperature, and strain sensor locations, data plots, wire routings, and a comparison between STS-107 and three other *Columbia* missions (STS-073, -090, -109) through EI+1000 sec. All five sheets use a common color-coding scheme to represent sensor status (nominal, off-nominal, off-line). They also contain one or more applicable vehicle drawings/schematics to aid in visualizing sensor locations and wire runs as known at the time of product release.

- A 40-page booklet (a.k.a. quantitative report) containing similar OI and MADS sensor information to the poster but with more detail including closeout photos, sensor information spreadsheets, 3D CAD model pictures, cable burnthrough timing plots, and data plot grouping based on future analysis efforts.

- Presentation charts containing similar OI sensor information to the poster and booklet but in a concise presentation format. Two sets of charts exist, the first involving various OI sensors through LOS and the second involving the same OI sensors through the post-LOS time period.

Several key inputs were used to generate this product:

- Raw OI and MADS sensor data from the MER
- Product VDM-P06: 3D Orbiter CAD Modeling
- Product VDM-P07: Wire Routing/Sensor Placement Reconstruction
- Product VDM-P09: Instrumentation Listing and Sensor Location
- Product VDM-P12: Wire Routing Details
- Product VDM-P13: Closeout photos
- Master entry timeline

The raw OI and MADS sensor data used to create the P04 product was acquired in electronic form (CSV format) directly from the MER as soon as it became available. The data was then manipulated and plotted (i.e. reduced) by the P04 product team while concurrently identifying/verifying all active sensors on the vehicle. This process was repeated multiple times until confidence in the data sets reached a high level and the product reached its final state of maturity. To ensure accuracy, results were spot-checked by independent reviewers from other VDM product teams through comparison to hardcopy plots created in the MER. In addition to being used directly in the P04 product, the raw and reduced sensor data was also distributed to the following recipients/teams to save time, ensure consistency, and minimize data processing overhead in the MER:

- Product VDM-P01: 3D Full Animation Event Sequence Playback
- Product VDM-P05: 2D Graphical Events Sequence
- Data Review and Timeline Reconstruction Team
- Failure Scenario Team
- *Columbia* Accident Investigation Board (CAIB)

As of this writing, rev 6 is the latest version of the poster and booklet, and rev 5 is the latest version of the presentation charts, all of which correspond to rev 15 of the master entry timeline.

An organized list of all electronic files on the VDM team share drive related to product VDM-P04 and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.5 VDM-P05: 2D Graphical Events Sequence

Product VDM-P05 is a set of presentation charts depicting the overall sequence of events during *Columbia's* entry in a graphical step-by-step manner. The heart of the product is a top-level drawing of the Orbiter, with sensors of interest shown highlighted in their approximate X-Y-Z location and color-coded according to their readings relative to nominal values. Sensor color-coding is as follows, with nominal values defined by the individual subsystem PRT's (with oversight from the Data Review and Timeline Reconstruction Team):

- Green = good sensor with nominal readings
- Yellow = sensor off-nominal high (for temperature, 0°F<ΔT<15°F)
- Orange = temperature sensor is off-nominal high, 15°F<ΔT <30°F
- Shaded Red = temperature sensor is off-nominal high, 30°F<ΔT <100°F
- Solid Red = temperature sensor is off-nominal high, ΔT >100°F
- Light Blue = temperature sensor is off-nominal low, ΔT <0°F
- Shaded Blue = sensor has experienced wire damage, readings no longer represent reality
- Solid Blue = sensor has experienced wire damage, readings have gone off scale and no longer represent reality

To provide a more complete view of the Orbiter, the product is separated into two distinct parts. Each part can stand-alone or be combined for greater insight. Part 1 shows the vehicle from above ("plan view" looking at the X-Y plane), including all sensors and wire runs as viewed from that perspective for each event depicted. It also includes a ground track map to show the exact location of the Orbiter above the earth, corresponding altitude and Mach number information, and an indication of how many sensors went offline in each of the three main wire bundles routed through the left wing (i.e. those running down the outboard and forward walls of the wheel well, sometimes referred to as bundles A, B, and C). Part 2 shows the vehicle from the port side (side view looking at the X-Z plane), including all sensors and some wire runs for each event depicted in part 1. It also includes an embedded plot of the highlighted sensor's output during a longer portion of the entry profile to give a broader view of trending at that sensor's location. Finally, a three dimensional perspective is shown from behind the vehicle to illustrate vehicle attitude.

Several key inputs were used to generate this product:

- Product VDM-P04: 2D Static Storyboard
- Product VDM-P09: Instrumentation List and Sensor Location
- Product VDM-P10: Sensor Signal Characterization (including the MADS sensor signature database)
- Product VDM-P13: Wire Routing Details
- Master entry timeline

This product went through many revisions, being continually updated as new information became available. Initial versions contained only a few sensors, all of which were OI measurements in the left wing and wheel well showing anomalous behavior during entry. As time passed and more information was obtained, additional sensors and other details were added, eventually expanding the scope of the product to include MADS and OI sensors, key wire runs, aerodynamic events, communication events, and debris events. As of this writing, rev 7 is the latest and intended final version of this product. It utilizes information from master entry timeline rev 17, MADS sensor signature database rev 4, and wire routing details through May 20, 2003.

In its final form, this product provides valuable insight into the sequence of events during entry by allowing a quick flip-through of the charts to visualize: (1) initial heating on the left wing leading edge, (2) heating/burnthrough of the sensor cables routed on the back side of the WLE spar, (3) heating/burnthrough of the sensor cables routed on the outboard and forward walls of the wheel well, (4) temperatures increasing inside the wheel well, and (5) heating/burnthrough of sensor cables routed inside the wheel well.

An organized list of all electronic files on the VDM team share drive related to product VDM-P05 and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.6 VDM-P06: 3D CAD Modeling

Product VDM-P06 is a complete solid model representation of *Columbia's* left wing, including wing structure, wheel well structure, main landing gear, hydraulic lines, select OI sensors and associated wire runs, and leading edge reinforced carbon-carbon (RCC) panels. Some areas and features of the mid fuselage are also included. Note that this model represents the "as-designed" vehicle and does not attempt to recreate the "as-built" configuration, with the exception of certain OI sensor locations that were modified according to inputs from key KSC personnel with first-hand knowledge of the vehicle hardware configuration.

Several key inputs were used to generate this product:

- Product VDM-P07: Wire Routing/Sensor Placement Reconstruction
- Product VDM-P12: Wire Routing Details
- Engineering drawings from the Shuttle Drawing System (SDS)
- Hardcopy engineering drawings

NASA-JSC personnel coordinated the modeling effort. Additional inputs were provided from a variety of different NASA and Boeing organizations as follows:

Contributing Organization	Models Created/Provided
NASA-JSC Structural Engineering Division (ES), with assistance from Lockheed Martin support contractors	RCC Panels Spar Fittings Wing Spars Wing Ribs Main Landing Gear
NASA-KSC Shuttle Engineering Group	Wing Wiring Main Landing Gear
Boeing-Huntington Beach Structures Group	Mid Fuselage Structure Main Landing Gear Door Wing Glove Ribs Elevon Ribs and Actuators
Boeing-KSC Structures Group	Wheel Well Hydraulics Wing Tile Carrier Panels
Boeing-KSC Design Visualization Group	Main Landing Gear Uplock Mechanism
NASA-JSC Energy Systems Division (EP)	Mid Fuselage Tanks and Fluid Lines
NASA-MSFC	RCC Panel Fittings

The master model exists in Pro/Engineer format and resides in an Intralink database at JSC (Root Folder\Space Shuttle\Accident Investigation\Top Level\V070-000002_012_gen_assy.asm). Mirror sites exist at KSC, MSFC, and Boeing-HB. The overall assembly currently contains over 2000 individual components, models of which have different levels of fidelity. Early on, "envelope" models approximating basic component geometry were built. In some cases these models were sufficient. However, in most cases additional details were later added at the request of the model end-users. Models are named using their part numbers, and the assembly is structured to match the Orbiter drawing tree.

As part of the overall CAD modeling effort, detailed models were created for much of the fluid systems hardware located in the mid fuselage region of the Orbiter. This effort was undertaken to develop a better representation of the vehicle in areas of potential interest, particularly those that may have been affected by off-nominal port fuselage sidewall temperatures. Models were developed for the Power Reactant Storage and Distribution (PRSD) tanks and select feedlines, in addition to the Main Propulsion System (MPS) gaseous helium (GHe) tanks and the ECLSS gaseous nitrogen (GN2) tanks located on the port side of the vehicle in mid-fuselage bays 7 though 11. These models were originally intended for integration into the overall vehicle assembly model. However, as it turns out, these components and areas were not of sufficient interest to warrant inclusion of these models.

Another aspect of the CAD modeling effort involved displaying the X-Y-Z locations of numerous OI and MADS sensors on the vehicle. Initial interest focused on OI sensors in the left wing, wheel well, and mid-fuselage areas. A total of 37 OI sensors were modeled as part of this activity, including the 14 sensors (seven left wing, seven left wheel well) that went OSL or unexpectedly changed state during entry prior to LOS. Later, additional OI temperature sensors from “area 40” on the vehicle were modeled after being identified as relatively sensitive external measurements that might provide additional insight into the local thermal environment. A total of 58 OI temperature sensors were modeled as part of this activity. Finally, after the recovery of the OEX recorder, a large number of MADS sensors were modeled based on relevance to the investigation. A total of 615 sensors were modeled as part of this activity, including pressure, temperature, and strain measurements throughout the vehicle. However, seven more sensors of interest were not modeled due to lack of location information.

For both OI and MADS sensors, X-Y-Z locations were obtained from a variety of sources, some of which were incomplete or in conflict with others. Best attempts were made to determine accurate locations when conflicts were present, and multiple checks were made to maximize accuracy of the final product. Although this was a CAD modeling task, the results of the effort relate directly to product VDM-P09 (Instrumentation Listing and Sensor Location) discussed in section 3.9. Accordingly, all files summarizing the sensors modeled and the associated X-Y-Z locations are kept with other VDM-P09 documents.

An organized list of all electronic files on the VDM team share drive related to product VDM-P06 and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report. In the case of product VDM-P06, all electronic files are in Pro/Engineer format and are maintained in a separate JSC Intralink database.

3.7 VDM-P07: Wire Routing / Sensor Placement Reconstruction

Product VDM-P07 consists of three sets of charts intended to organize and consolidate the large volume of design, installation, functionality, and performance information related to the *Columbia* investigation that resides on the VDM team share drive. These files emphasize graphical display methods (3D CAD models, wire routing drawings, closeout photographs, etc.) to aid in visualizing hardware installation. Initially, key information was posted on the walls of the VDM team headquarters and incrementally provided to the OVEWG. Subsequently, this information was organized into a set of more detailed "hardware description" charts for distribution to the OVEWG and CAIB.

Several key inputs were used to generate this product:

- Product VDM-P06: 3D CAD Modeling
  - Pro-E integrated CAD model of OV-102 (pulled from JSC Intralink 3/11/03_8:00am)
- Product VDM-P12: Wire Routing Details
  - Boeing-HB plan view wire routing stick drawings (wing1_Rev4.ppt)
  - Boeing-HB wire routing blacklines (wing2part1_rev0.ppt, wing2part2_rev0.ppt, WIRE RUN SKETCH.ppt)
  - P105 Pinout Rev0_Galvez.ppt
  - Boeing-HB wheel well isometric (wheel well isometric-Rev4.ppt)
  - Boeing-HB wire routing blacklines (V070-796051 LMLG Dark Line Rev4 Pt 1 of 3.ppt)
  - Boeing-HB Wheel Well Plan View (Wing-wheelwell-Rev4.ppt)
- Product VDM-P13: Closeout Photos
  - OV-102 photographs from the Palmdale Orbiter Major Modification (OMM)
  - OV-102 KSC close-out photographs from SIMS
- Left wing and wheel well vent and leak path information provided by Boeing-Houston (Maingearwellvent_info3.xls)

An organized list of all electronic files on the VDM team share drive related to product VDM-P05 and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report. In the case of product VDM-P07, no further revisions of the hardware description charts are planned even though several key inputs, particularly those related to product VDM-P12 (Wire Routing Details), have already been appended or revised.

3.8 VDM-P08: Events Timeline

Due to the importance of the master entry timeline as an input to many of the VDM team products, this product consisted of assigning a VDM team member to be a liaison to the Data Review and Reconstruction Timeline Team. Although no electronic files were created, this product ensured a thorough understanding of the timeline team's products and conveyed VDM team needs, questions, and comments directly to the timeline team.

3.9 VDM-P09: Instrumentation Listing and Sensor Location

Product VDM-P09 consists of instrumentation system schematics and master measurement lists (MMLs) for all OI and MADS sensors on *Columbia* during STS-107. This information was used as a basic and critical input to many VDM team products, particularly those that involved data plotting, sensor signature characterization and trending analysis, and commonality assessment between measurements. Attributes of primary interest for each measurement included MSID, description, sensor type and X-Y-Z location, power supply and signal conditioner assignments, engineering units and range, sample frequency and most/least significant bit, etc. Since all of this information cannot be found in a single source for OI or MADS sensors, numerous files are used to capture the intent of this product.

Several key inputs were used to generate this product, some of which became part of the product itself due to complexity associated with file and database consolidation:

- For OI sensors:
    - Orbiter Instrumentation Program and Components List (ICPL), Orbiter 102, Flight 28, STS-107, dated 10/29/01
        - Volume one (Equipment List)
        - Volume two (Signal Conditioner and Telemetry Loading List)
        - Volume three (PCM MUX and downlink formats)
    - Electronic database version of the IPCL maintained at Boeing-HB
    - JSC 18366: Operational Instrumentation, Space Shuttle Orbiter, Temperature Measurement Locations, revised January 1992
    - Electronic MML Notebook on Boeing-KSC, NASA Systems website (http://p51.ksc.nasa.gov/aps/mml/)
- For MADS sensors:
    - JSC 23560 Modified for STS-107 (OV-102) Investigation: Modular Auxiliary Data System (MADS) / Orbiter Experiments (OEX) Measurement Locations, dated 4/16/03
- For all sensors:
    - Shuttle drawing system (SDS)

Inconsistencies exist between the items listed above, particularly with respect to sensor X-Y-Z location. Despite this conflict, an attempt was made to document the exact X-Y-Z locations used for sensor placement in product VDM-P06 (3D CAD Modeling) and correlate these placements to their respective sources. As of this writing, a supplemental action external to the VDM team exists to resolve any conflicts and consolidate all attributes mentioned above into a single source.

An organized list of all electronic files on the VDM team share drive related to product VDM-P09 and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report. In the case of product VDM-P09, some of the files are just electronic versions of the documents mentioned above.

3.10 VDM-P10: Sensor Signal Characterization For Failure Scenario

Product VDM-P10 consists of a failure mode assessment for various OI and MADs sensors and associated signal conditioners on the vehicle. As such, the intent of this product was met through a combination of analysis and testing.

Analysis, described in this section, involved predicting sensor/signal conditioner outputs for a variety of fail-open and fail-short conditions based on a detailed knowledge of instrumentation system hardware configuration and functionality, along with past experience. In this case, efforts focused on a subset of the 14 OI sensors (seven left wing, seven left wheel well) that went OSL or unexpectedly changed state prior to LOS. This subset included five hydraulic system line/component temperatures in the wing and two tire pressures in the wheel well. For the temperatures, OSL readings were only predicted to be possible under certain fail-short conditions. For the tire pressures, OSL readings were predicted to be possible under both fail-short and fail-open conditions.

Testing, described in section 3.15, involved non-destructive open/short tests with actual sensors and flight-like signal conditioners to confirm analytical predictions. It also involved wire burnthrough tests with flight-representative cables, bundles, and harnesses in a variety of environments and configurations to recreate sensor output signatures observed during entry. As also mentioned in section 3.15, testing showed that breakdown in the Kapton insulation on the sensor wires at temperatures beginning at 750 °F produces a gradual decrease in resistance between adjacent conductors in a cable and adjacent cables in a bundle, eventually creating a hard-short condition that results in the predicted and observed OSL outputs.

An important extension of this product involved analyzing and interpreting/characterizing MADs sensor signatures to explain erratic behavior and address concerns about data validity. The primary objective was to establish a single point in time beyond which (or a range of time during which) the data for each relevant MADS sensor can be considered unreliable (a.k.a. “unphysical”). This was accomplished by first segregating the data according to measurement and sensor type. Examples include resistance temperature devices (RTDs) vs. thermocouples for temperature, Statham vs. Kulite transducers for pressure, and full-bridge gauges for strain. Then, failure modes and commonalities between the sensors were examined to explain the data observed. The result of this activity was a spreadsheet (referred to as the MADS sensor signature database) and set of charts to describe and categorize sensor signatures, define sensor commonalities, and identify the point (or range) in time where sensor data is considered invalid.

A further development of this effort involved using the MADS sensor signature database, instrumentation and sensor location data from product VDM-P09, and wire routing information from product VDM-P12 to correlate MADS sensor failure timing with wire run locations, particularly along the WLE spar. This activity is described in detail in section 3.16.

An organized list of all electronic files on the VDM team share drive related to product VDM-P10 and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report. Note that all files related to testing are contained in section 3.15 and all files related to the WLE wire run assessment are contained in section 3.16.

3.11 VDM-P11: Structure / Installation Drawings

Product VDM-P11 no longer exists in the VDM team product flowchart. Its intent is effectively captured by products VDM-P06 (3D CAD Modeling) and VDM-P07 (Wire Routing / Sensor Placement Reconstruction (Drawings/Photos)).

3.12 VDM-P12: Wire Routing Details

Product VDM-P12 consists of simplified two-dimensional “stick” drawings and detailed three-dimensional “blackline” drawings to document sensor installation, wire routing, and connector pin-out details for all failed and non-failed OI and MADS sensors in the left wing and wheel well. Blackline drawings were created from engineering drawings and engineering orders (EOs) residing in the SDS. Closeout photos taken during *Columbia’s* third and most recent OMM (J2) at Boeing-Palmdale were also used to confirm sensor placements and wire routing details.

The task of gathering all the necessary information was broken down into areas and functions. Initial assessment involved the following items:

- Failed and non-failed OI sensors and wiring in the wing
- Failed and non-failed OI sensors and wiring in the wheel well
- Failed and non-failed end-effector power and control wires in the wing
- Failed and non-failed end-effector power and control wires in the wheel well

Significant findings of this initial effort included a determination that all seven OI measurements failing OSL in the wing were contained in a common wire bundle routed along the outboard and forward walls of the wheel well (one of three major bundles, sometimes referred to as A, B, and C). It was also determined that wires for these same sensors were routed through a common connector (P105) in the midbody interface connector panel located in the wing glove area (on the Yo-105 bulkhead between the Xo980 and Xo1009 spars). Other OI sensors not lost but located nearby did not share common wire routings with the failed OSL sensors. Additional indications were that six of the seven affected measurements in the wheel well shared common wire runs to the wheel well interface connector panel. The seventh measurement shared portions of the same wire run but went to a different connector on the panel.

After the OEX recorder was recovered, the product scope was expanded to include stick drawings for all remaining sensors in the wing plus select blackline drawings of sensor installations and wire routings near the left WLE spar. This last task was necessary to support the Failure Scenario Team. The investigation of MADS sensors was by far the biggest effort of the wire routing team. Upon completion, it consisted of eleven batch files of strain gauge measurements (147 measurements total), seven batch files of wing pressure measurements (80 total), two batch files of wing and Orbital Maneuvering System (OMS) pod temperature measurements (23 total), and one acoustic sensor.

The total effort was divided among numerous engineering groups at KSC, JSC and Boeing-HB. Wire routing information was also used by KSC Orbiter Electrical (OEL) personnel for incorporation into their Pro/Engineer model that depicted key OI sensor wire runs, which was eventually incorporated into product VDM-P06 (3D CAD Modeling).

One interesting observation was that some of the blackline drawings conflict with the closeout photos taken during *Columbia's* last OMM. This is most likely due to flexibility in the way the wiring is installed in the vehicle, which pertains to the accessibility of the intended wire routing and the amount of wire the supporting fixtures (cable clamps, aluminum tape, etc.) can handle.

An organized list of all electronic files on the VDM team share drive related to product VDM-P12 and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.13 VDM-P13: Closeout Photos

Product VDM-P13 consists of an organized collection of photos, some available electronically and some not, to help define or confirm structural configurations, sensor locations and installation details, and wire runs applicable to other VDM team products. Where possible, OV-102 closeout photos taken just prior to the STS-107 mission or just after the last OMM (J2) were used as the preferred source of information for this purpose. However, OV-102 original build photos and other vehicle photos were also used as needed, with an acknowledged sense of uncertainty regarding the applicability to OV-102.

The overall photo collection created under product VDM-P13 includes some photos that are available in electronic form and some that are not. Sources of electronic photos include:

- The USA-KSC Still Image Management System (SIMS) website (http://kscgrndtsk1/SIMS/sims.htm)
- The NASA-KSC Investigation Links website (http://www-launchops.ksc.nasa.gov/etd/Investigation/Links.shtml)

Local copies of particularly relevant photos from these websites also reside on the VDM team share drive. Other photos are available electronically on CD or are available in hardcopy form only. An inventory of all photo items generated and tracked by the VDM team as part of product VDM-P13 is contained in Appendix C. As of this writing, all relevant photos have been retrieved and distributed so no additional work is planned on this product.

3.14 VDM Team ASA4 Anomaly Assessment

The aerosurface servoamplifier assembly #4 (ASA4) anomaly was discovered during review of the OI sensor pre-LOS data, which showed that the channel 4 position feedback signal on the speedbrake began to rise unexpectedly in the last three data samples before LOS, indicating speedbrake opening. However, the commanded and expected position of the speedbrake during entry is closed, as observed prior to this time. Post-LOS data showed the following additional anomalous events:

- Speedbrake position indication was bleeding off towards null.
- Right and left inboard and outboard elevon channel 4 isolation valves went to bypass
- A force fight occurred between channels 1-3 and channel 4 on the left outboard elevon for approximately 2 seconds
- Remote power converters (RPCs) that provide main power (bus A & C) and isolation valve power (bus B) to ASA4 both tripped

Upon discovering these events/conditions, a small group of VDM team members with expertise in flight control hardware, hydraulics, and electrical power distribution and control (EPDC) system hardware performed a root cause assessment for this anomaly. The first task was to gain a thorough understanding of the power/control circuits and functionality of the channel 4 flight control actuators. This was accomplished by mapping the wire routing for these signals and investigating the inner workings of the ASA4 box and associated actuator sensors/transducers. During this process, the following significant details were discovered:

- ASA4 receives DC power from three separate RPCs. Primary power is supplied by main buses A and C “OR’d” together through a diode logic circuit. Isolation valve power is supplied to ASA4 by main bus B.
- Excitation power (26 VAC) to the actuator position feedback and delta pressure transducers is derived internal to ASA4 from the main bus A and C feeds.

- Loss of DC power to ASA4 will cause the fail flags to be raised on all channel 4 actuators, thus causing the isolation valves to bypass (i.e. release channel 4 hydraulic pressure within the actuator power valve).
- Loss of excitation power to the actuator position feedback and delta pressure transducers will cause a transition in output to the null value
- Loss of DC power to the isolation valves will prevent valve bypass.
- Excitation wiring to the actuator position feedback and primary delta pressure transducers is separate from equivalent wiring to the secondary delta pressure transducer

After several detailed review meetings and discussions, the team concluded that the most likely events explaining the ASA4 anomaly were as follows:

- Two shorts occurred at approximately the same time due to burning wires between ASA4 and the left outboard elevon actuator
    - The first short involved the AC excitation power wires to the actuator position feedback sensor
    - The second short involved the DC power wires to the isolation valve
- The current-limiting feature of the RPCs feeding the shorts reduced the bus voltage to ASA4 with a corresponding degradation in ASA4 performance and eventual RPC trip
- The shorts combined with degraded performance of ASA4 and tripped RPCs resulted in a loss of AC power to the actuator position sensor and DC power to the isolation valve
    - Position feedback output transitions to null state starting a force fight
    - Isolation valve fails to bypass and end the force fight before RPC trip

In the end, these events were considered credible and consistent with the behavior of Kapton-insulated wires when exposed to a high heating environment. However, these events occurred very late in the entry timeline, had no negative effects on flight control performance at the time, and were a symptom of a larger problem involving hot plasma flow into the left wing.

An organized list of all electronic files on the VDM team share drive related to the ASA4 anomaly assessment and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

3.15 VDM Team Testing

The VDM team conducted nine separate test programs in support of the *Columbia* investigation. All nine test programs are summarized in this report, with additional test set-up details and test data available in separate reports and briefings contained on the

VDM team share drive and referenced in Appendix C. Important observations and/or conclusions resulting from each test program are also summarized below.

1. Main Landing Gear Uplock Release Cartridge Auto Ignition Test – ESTA

   This test was conducted at the Energy Systems Test Area (ESTA) at JSC. A class III main landing gear uplock release cartridge was placed in a thermal chamber and subjected to increasing temperature at 25 to 30 °F per minute until propellant ignition occurred. Results showed autoignition at 598 °F, far above any temperatures observed in the wheel well during entry.

2. Main Landing Gear (MLG) Proximity Sensor Failure Test – NSLD

   This test was conducted at the NASA Shuttle Logistics Depot (NSLD) at KSC. Proximity sensors in each wheel well detect uplock vs. downlock position of the main landing gear. Entry data from these sensors, included in the OI telemetry stream, showed an unexpected change of state from uplock to not-uplock on the left main gear uplock proximity sensor prior to LOS. To examine the failure modes of this sensor and its "proximity box" signal conditioner, a series of tests was run to characterize the output for simulated failures of the sensor cabling. Test conditions included various combinations of hard open circuits, hard short circuits, and soft short circuits for various combinations of conductors in the sensor cabling. Results showed which conditions provide a gear uplock vs. not - uplock output. Furthermore, it was determined that a soft short within a particular resistance range could cause a change in indicated output for a "target far" sensor like the one in question, but not for "target near" sensors like those that did not change state in flight. For this reason, it is presumed that the change of state in the left MLG downlock sensor is a false indication resulting from local heating/burning of the sensor wires.

3. Sensor / Signal Conditioner Failure Test – SAIL

   This test was conducted in the Shuttle Avionics Integration Laboratory (SAIL) at JSC. Entry data for numerous OI pressure and temperature sensors from before LOS showed unexpected output changes from nominal to OSL, some decaying quickly and others much more slowly. To examine the failure modes of these sensors (or equivalent electric circuits) and the associated signal conditioners, a series of tests was run to characterize the output for simulated failures of the sensor cabling. Test conditions included hard open circuits, hard short circuits, and soft short circuits for various combinations of conductors in the sensor cabling. Results showed those cable failures / combinations of failures that produce a normal, off scale high (OSH), or OSL output. More importantly, it was determined that multiple hard short and hard open combinations could produce an OSL output but always with a step-function signature. A smooth decay as seen in flight could only be produced under variable resistance conditions similar to those generated in the wire burnthrough tests (to be described in the following sections).

4. Initial Cable Burnthrough Characterization Test (oxygen-acetylene torch) – ESTA

   This test was conducted at ESTA at JSC. Early in the STS-107 investigation, evidence from OI sensors indicated a left wing overtemperature condition. Accordingly, a quick test was performed to determine the behavior of Kapton-insulated cables when subjected to localized heating from a small oxygen-acetylene torch. Although this heat source was recognized to be very different than the flight plasma environment, the objective of the test was simply to provide generic data on the behavior of Kapton-insulated cables when rapidly heated. Individual twisted shielded cables and small harnesses consisting of multiple twisted shielded cables were all heated with the torch. Temperature and resistance between conductors within a single cable were measured and recorded. Results from single cable testing showed that a short gradually develops between conductors when heated, with some finite time required for the short to propagate. Based on available literature for Kapton insulation, this behavior is caused by breakdown of the insulation at high temperature as it transitions to being a conductor. Results from the harness testing showed that there can be a significant time delay in the onset of a short circuit for different cables depending on the location within a harness. These factors are presumed to explain the variability in signal decay profile (i.e. time from nominal to OSL) and times at which signal decay began for each sensor.

5. Hot Oven Cable Overtemperature Test (GN2 Environment) – ESTA

   This test was conducted at ESTA at JSC. To supplement the initial cable burnthrough test, a hot oven test was performed to characterize the behavior of a longer section of a Kapton-insulated twisted shielded cable when uniformly heated. Single cables were individually subjected to heating in a 12 in long tube oven. Temperature and resistance between the conductors in the cable were recorded. A nitrogen purge was implemented to minimize potential reaction between oxygen and the cable materials at elevated temperature. Heating of the test cables was performed at various rates by adjusting oven settings. Results showed that the short circuit between conductors in a cable initiates at 750 to 950 °F. Results also showed that the propagation time for the short (from essentially infinite resistance to some very low value) was a strong function of heating rate; higher heating rates produced a shorter propagation time. Although this result was qualitative in nature, since heating rates were not actually measured, the observed behavior did relate to the *Columbia* flight data where sensor failures showed varying times to decay from a nominal reading to OSL. The conductor-to-conductor resistance data from this test was subsequently applied to the sensor calibration curves and results of the SAIL testing to show the predicted vehicle signal conditioner output if the sensor cables were subjected to an overtemperature condition like that simulated in the oven. The resulting plots of these simulated flight measurements showed a very similar profile to the flight data.

6. Hot Oven Cable Overtemperature Test (Vacuum Environment) – WSTF

   This test was conducted at the White Sands Test Facility (WSTF). Since the off-nominal sensor signatures were observed with the vehicle at such a high altitude, portions of the hot oven GN2 test were repeated at vacuum conditions to evaluate any effects of ambient pressure. Again, single Kapton-insulated twisted shielded cables were individually subjected to heating in a long vacuum oven with temperature and resistance between conductors measured and recorded. As expected, results showed the same resistance decay profile as seen during the hot oven tests in GN2, thus supporting previous conclusions.

7. Cable Burnthrough Thermal Model Calibration Test (small propane torch) – ESTA

   This test was conducted at ESTA at JSC. Early on in the investigation, the analysis team developed detailed thermal models of Orbiter cables, harnesses (multiple cables), and bundles (multiple harnesses) being impinged upon by hot gas flow. Cable and harness burnthrough testing was subsequently performed to provide engineering data to correlate/calibrate these thermal models. Various Kapton-insulated twisted shielded cables and 40-cable harnesses were heated with a small propane torch from various distances and incident angles to vary the local heat rates. Instrumented metal specimens, consisting of steel rods and tubes to simulate the size and shape of the flight cables and harnesses, were also heated with the torch and used as a calorimeter. Temperature and resistance between conductors within the cables and harnesses were recorded, as were numerous temperatures within the calorimeters. Results were used to support initial development and correlation of the thermal models. However, the small torch size was insufficient to allow testing of a large bundle similar in size to those carrying the sensor signal and excitation wires in the wing and wheel well areas. Therefore, complete thermal model calibration was not yet possible.

8. ESTA Cable and Bundle Burnthrough Test (large propane torch)

   To enable additional burnthrough testing on a large wire bundle representative of those being modeled/analyzed on the vehicle, a larger propane torch was used. Test bundles of 1.75 in diameter, consisting of 290 Kapton-insulated twisted shielded cables, were also built from flight spare inventory to simulate the wire bundles routed along the forward and outboard walls of the wheel well. Within each test bundle, temperature and resistance between conductors were measured and recorded on 33 individual cables. These bundles, along with instrumented metal calorimeters built to simulate the size and shape of large bundles, were then individually heated with the torch. Results were used to complete development and correlation of the thermal models.

9. Arc Jet Cable Bundle Failure Test

   This test was conducted in the Atmospheric and Reentry Materials Structural Evaluation Facility (ARMSEF) at JSC. During STS-107, many OI and MADS sensors showed anomalies in their output signals, likely related to localized cable heating. In this test, cable bundles simulating those carrying numerous OI and MADS sensor wires on the Orbiter were subjected to hot plasma impingement representative of the entry environment through various sized holes in an aluminum plate. The test bundles were approximately 1.75 in diameter and consisted of 290 separate 24 AWG, Kapton-insulated, twisted, shielded cables secured with flight-like aluminum cable clamps. Within each bundle, 33 separate cables were monitored for changes in conductor-to-conductor resistance as a function of temperature and time.

   The general purpose of the test was to gain an understanding of the convective heating environment and associated thermal failure mechanism for the cable bundles routed inside the left wing. The specific objective was to obtain the failure mechanism characteristics, failure initiation time, failure rate, and burn-through time for a cable bundle subjected to a representative plasma environment. Test results showed that arc jet plume heating could produce the same cable failure mechanism seen in previous torch tests (but much more quickly and dramatically) and the same sensor output signatures seen in flight. They also showed a very rapid erosion of the hole in the aluminum plate with a corresponding increase in cable failure rate. Finally, test-derived heating rate and cable failure rate data can be used to validate thermal models of the vehicle to support failure scenario development for the *Columbia* investigation.

3.16 VDM Team Leading Edge Wire Run Assessment

As an extension of product VDM-P10 (Sensor Signal Characterization for Failure Scenario), a detailed assessment was performed to examine the correlation between MADS sensor failure timing and sensor wire routing. The MADS sensor signature database from product VDM-P10 and wire routing information from product VDM-P12 were both used as inputs to this assessment.

Results of the assessment indicate that all 18 MADS sensors with wires contained in one of the five separate harnesses routed along the left WLE spar (sometimes referred to as A, B, C, D, and E) were lost. Furthermore, 17 out of 18 of these events occurred during a 10 sec time interval (EI+487 sec to EI+497 sec) preceding the loss of any other MADS sensors with different wire routings. The only exception involved four unrelated MADS sensors sharing a common power supply with the failed WLE-routed sensors. These four sensors are presumed to have been lost due to electrical commonality, not wire heating/burning away from the left WLE spar. Finally, wire routing geometry and sensor failure order (top to bottom, outboard to inboard) suggest specific boundaries for left WLE spar burnthrough behind RCC panel 8.

Based on engineering drawings and closeout photos, some uncertainty still exists regarding which sensor wires are contained in which of the five main WLE harnesses. The most notable example involves the WLE spar temperature sensor behind RCC panel 9, which was the last of the 18 WLE-routed sensors to fail and did so even after other MADS sensors in the three main wheel well wire bundles began to fail. Despite this uncertainty, confirmed information about the wire routing still provides strong evidence that a breach in the WLE spar occurred at RCC panel 8, allowing hot plasma to enter the wing.

The product resulting from this assessment is a set of presentation charts containing a tabular summary of all WLE-routed MADS sensors, a 3D CAD picture showing sensor locations and cable routings, closeout photos confirming these routings to the extent possible, and relevant plots of sensor data. This information is kept on the VDM team share drive and is also referenced in Appendix C.

3.17 VDM Team Miscellaneous Tasks

Several miscellaneous tasks were performed by select VDM team members based on expertise in Orbiter propulsion and power subsystems, including the Auxiliary Power Unit (APU); Electrical Power Distribution and Control (EPDC) System; Fuel Cells (FC); Hydraulics/Water Spray Boiler (Hyd/WSB); Main Propulsion System (MPS); Orbital Maneuvering System (OMS); Power Reactant Supply and Distribution (PRSD) System; Pyrotechnic Devices (Pyro); and Reaction Control System (RCS). In particular, hardware inventories and hazard assessments applicable to STS-107 were created to aid the debris recovery teams with hardware identification and handling safety. In addition, pre-flight data records that are not controlled (i.e. organized and stored) in any other configuration management system were identified and impounded, including Pyro acceptance data packages (ADPs) and Space Shuttle Engineering Integration (SSEI) flight readiness statements (FRSs).

An organized list of all electronic files on the VDM team share drive related to the miscellaneous tasks and applicable to this report is contained in Appendix C. Collectively, these files constitute the product itself, or they represent the product if not computer-based or not available in a compatible electronic format. They also contain supplemental information that describes or explains important product content, inputs/outputs, observations, and results/conclusions in much greater detail than this report.

4.0 CONCLUSIONS AND SIGNIFICANT FINDINGS

The VDM team charter included the creation of unique and innovative data display products that aid in understanding the hardware configuration, sensor response data, and complex sequence of events during *Columbia's* entry. Accordingly, the team focused on producing the products defined by the VDM team product flowchart in Appendix A and responding to all related action items listed in Appendix B. All VDM team products have been described in this report. Action items were not discussed but relate directly to the VDM team products as indicated by the action tracking number and associated closeout files in Appendix B. Since the VDM team was not formally tasked with detailed interpretation of the flight data, significant findings are limited to those areas in which testing or analysis took place to create a product, pursue a special activity, or respond to an action. The resulting list of conclusions and findings is shown below. Most of these items have previously been discussed in this report.

- The VDM team produced seven major products and six supporting data generation/gathering products. Four special activities related to these products and encompassed by the VDM team charter were also pursued. Finally, the VDM team worked 98 formal action items. The content, revision status, and findings of each VDM team product and special activity were previously discussed in this report. As of this writing, only two action items remain open. The first involves plasma impingement testing of flight-representative cable bundles under VDM Team Testing (section 3.15). The second involves production of the latest and expected final revision of product VDM-P01 (3D Full Animation Event Sequence Playback, section 3.1).

- The first OI indications of off-nominal system performance involved a hydraulic line temperature on the inboard sidewall (Yo-105) of the left wheel well (V58T1703A, LMG Brake Line Temp D) at GMT 2003/032:13:52:17. Subsequently, other OI sensors began showing off-nominal trends. Of these, a total of 14 OI measurements went OSL or unexpectedly changed state (starting at GMT 2003/032:13:52:56) prior to LOS, as listed in section 3.0. Seven of these sensors were located in the left wing and seven were located in the left wheel well. All seven in the left wing shared a common wire bundle routed along the outboard and forward walls of the left wheel well. They also shared a common connector panel and connector in the wing glove area (midbody interface connector panel located on the Yo-105 bulkhead between the Xo980 and Xo1009 spars, connector P105). Six of the seven in the wheel well shared a common wire run along the aft wall (Xo1191 spar), ceiling, and forward wall (Xo1040 spar) of the wheel well, with the seventh signal sharing portions of this same run. All seven of these signals shared a common connector panel in the wheel well (wheel well interface connector panel located on the Y-105 bulkhead) but they did not all share a common wire bundle or connector.

- Recovery of the OEX recorder provided 600+ additional MADS pressure, temperature, and strain measurements of interest to the investigation, the first of which (V12G9921A, Left Wing Front Spar Strain) began showing signs of off-nominal performance at GMT 2003/032:13:48:39, approximately 3:38 sec before the first off-nominal OI sensor reading was detected.

- Based on analysis and testing performed by the VDM team, nearly all notable OI and MADS sensor signatures observed during entry (OI sensors lost OSL or unexpectedly changing state before LOS, MADS sensors showing erratic behavior then failing OSL or OSH, OI sensors indicating the ASA4 anomaly, etc.)

are consistent with plasma-induced heating/burnthrough and progressive shorting of the associated Kapton-insulated cables, rather than actual events occurring at the location of each sensor. Propagation of the short, as manifested in failure start time and signal decay time, is dependent on cable location within a harness/bundle and local heat flux, with arc-jet plasma impingement tests showing the greatest similarity to flight data.

- Product VDM-P05 (2D Graphical Events Sequence) provides an excellent overall view of the sequence of events that occurred during entry. The format and content of this product allow a quick flip-through of the charts to visualize: (1) initial heating on the left wing leading edge, (2) heating/burnthrough of the sensor cables routed on the back side of the WLE spar, (3) heating/burnthrough of the sensor cables routed on the outboard and forward walls of the wheel well, (4) temperatures increasing inside the wheel well, and (5) heating/burnthrough of sensor cables routed inside the wheel well. When combined with product VDM-P04 (2D Static Storyboard), a comprehensive view of all events and sensor data observed during entry is obtained.

- A comprehensive 3D solid model representation of the Orbiter's left wing was created in Pro/Engineer under product VDM-P06 (3D CAD Modeling). The top-level assembly file contains over 2000 individual components, including wing structure, wheel well structure, main landing gear, hydraulic lines, OI sensors and associated wire runs, and leading edge RCC panels. Additional modeling was performed to show fluid systems hardware located in the mid fuselage area adjacent to the left wheel well, in addition to 37 OI sensors in the left wing, wheel well, and mid-fuselage areas; 58 OI temperature sensors in area 40; and 615 MADS pressure, temperature, and strain sensors throughout the vehicle.

- An extension of product VDM-P10 (Sensor Signature Characterization for Failure Scenario, section 3.10) involved analyzing and interpreting/characterizing MADs sensor signatures to explain erratic behavior and address concerns about data validity. The result of this activity was a comprehensive sensor signature database representing MADS sensor failure signatures and timing. Related work on the leading edge wire run assessment (section 3.16) indicated that all 18 MADS sensors with wires contained in one of the five separate harnesses routed along the left WLE spar were lost. Furthermore, 17 out of 18 of these events occurred during a 10 sec time interval (EI+487 sec to EI+497 sec) preceding the loss of any other MADS sensors with different wire routings. The only exception involved four unrelated MADS sensors sharing a common power supply with the failed WLE-routed sensors. These four sensors are presumed to have been lost due to electrical commonality, not wire heating/burning away from the left WLE spar. Finally, wire routing geometry and sensor failure order (top to bottom, outboard to inboard) suggest specific boundaries for left WLE spar burnthrough behind RCC panel 8.

APPENDIX A: VDM Team Product Flow Chart

APPENDIX B: VDM Team Roster and Action List

NOTE:

Closeout files referenced in the VDM team action list are available in the final report folder on the VDM team share drive and on the final report CD. However, unlike the product document list in Appendix C, embedded hyperlinks to the action closeout files are not present. Instead, base filenames and file extensions are given without regard to revision or date. This was done to minimize action list upkeep as response files were continually being revised. For those files that are common to both lists, hyperlinks to the revision available at the time of this writing can be accessed from the product document list in Appendix C. For those that are not common (with the exception of 100+ MB raw data files associated with product VDM-P04), the base filenames and file extensions can be used to locate a particular document of interest in the final report folder on the VDM team share drive or on the final report CD (or better yet, the related product folder on the VDM team share drive where the latest revisions of all VDM files are kept).

APPENDIX C: VDM Product Files for the Final Report

Product/Activity	Files Applicable to VDM Final Report?
VDM-P01: 3D Full Animation Event Sequence Playback	YES
VDM-P02: Physical Mockup	YES
VDM-P03: 3D Graphical Events Sequence	NO
VDM-P04: 2D Static Storyboard	YES
VDM-P05: 2D Graphical Events Sequence	YES
VDM-P06: 3D CAD Modeling	YES
VDM-P07: Wire Routing / Sensor Placement Reconstruction (Drawings/Photos)	YES
VDM-P08: Events Timeline	NO
VDM-P09: Instrumentation Listing and Sensor Location	YES
VDM-P10: Sensor Signal Characterization For Failure Scenario	YES
VDM-P11: Structure / Installation Drawings	NO
VDM-P12: Wire Routing Details	YES
VDM-P13: Closeout Photos	YES
VDM Team ASA4 Anomaly Assessment	YES
VDM Team Testing	YES
VDM Team Leading Edge Wire Run Assessment	YES

APPENDIX D: Acronyms and Abbreviations

Acronym/Symbol	Definition
Δ	Delta
2D	2-Dimensional
3D	3-Dimensional
AC	Alternating Current
Actr	Actuator
ADP	Acceptance Data Pack
APU	Auxiliary Power Unit
ARMSEF	Atmospheric and Reentry Materials Structural Evaluation Facility at JSC
ASA	Aerosurface Servo Amplifier
AVI	Audio Video Interleave
AWG	American Wire Gauge
CAD	Computer
CAIB	*Columbia* Accident Investigation Board
CD	Compact Disk
CSV	Comma Separated Variable
DC	Direct Current
DVD	Digital Video Disk
ECLSS	Environmental Control and Life Support System
EI	Entry Interface
Elev	Elevon
EO	Engineering Order
EP	Energy Systems Division at JSC
EPDC	Electrical Power Distribution and Control
ES	Structures and Mechanics Division at JSC
ESTA	Energy Systems Test Area at JSC
FC	Fuel Cell
FDM	Frequency Division Multiplexer
FRS	Flight Readiness Statement
GHe	Gaseous Helium
GMT	Greenwich Mean Time
GN2	Gaseous Nitrogen
HB	Huntington Beach, CA
Hyd/WSB	Hydraulics / Water Spray Boiler
IDI	Information Dynamics, Inc.
IGOAL	Integrated Graphic Operations and Analysis Laboratory at JSC
Inbd	Inboard
IPCL	Instrumentation Program and Components List
JPEG	Joint Photographic Experts Group
JSC	Johnson Space Center
KSC	Kennedy Space Center

LH	Left Hand
LMLG	Left Main Landing Gear
LMG	Left Main Gear
Ln	Line
LOE	Left Outboard Elevon
LOS	Loss of Signal
Lwr	Lower
MADS	Modular Auxiliary Data System
MEI	Muniz Engineering, Inc.
MER	Mission Evaluation Room
MLG	Main Landing Gear
MML	Master Measurement List
MPEG	Moving Pictures Experts Group
MPS	Main Propulsion System
MSFC	Marshall Space Flight Center
MUX	Multiplexer
NASA	National Aeronautics and Space Administration
NSLD	NASA Shuttle Logistics Depot at KSC
OEL	Orbiter Electrical
OEX	Orbiter Experiments
OI	Orbiter Instrumentation
OMM	Orbiter Major Modification
OMS	Orbital Maneuvering System
OSH	Off-Scale High
OSL	Off-Scale Low
Outbd	Outboard
OVEWG	Orbiter Vehicle Engineering Working Group
PCM	Pulse Code Modulation
Press	Pressure
Prox	Proximity
PRSD	Power Reactant Storage and Distribution
PRT	Problem Review Team
Pyro	Pyrotechnic
RCC	Reinforced Carbon-Carbon
RCS	Reaction Control System
RPC	Remote Power Controller
RTD	Resistance Temperature Detector
Rtn	Return
SAIL	Shuttle Avionics Integration Laboratory
SDS	Shuttle Drawing System
SIMS	Still Image Management System
SSEI	Space Shuttle Engineering Integration
STK	Satellite Took Kit
T	Temperature
TPS	Thermal Protection System

Upr	Upper
USA	United Space Alliance
VAC	Volts AC
VDC	Volts DC
VDM	Vehicle Data Mapping
WLE	Wing Leading Edge
WSTF	White Sands Test Facility

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